Deeply Virtual Compton Scattering off light nuclei:

a crossroad between hadronic and nuclear Physics toward the 3D nuclear imaging

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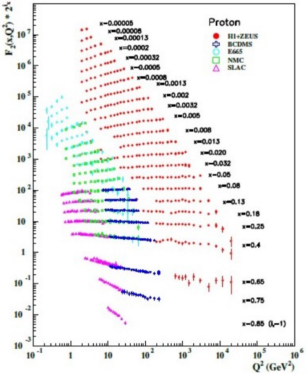
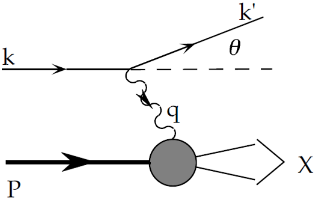
- **Introduction**
- **(Light) nuclei as a QCD laboratory**
- **Analysis of DVCS off ^{4}He**
- **Check and test of our models: comparison with JLab data**
- **Future perspectives for the hadronic Physics at the Electron Ion Collider (EIC)**
- **`TOPEG`: a Monte Carlo event generator for DVCS off light nuclei**

Introduction

Inclusive DIS process $A(e,e')X$, $Q^2 = -q^2$

$$\frac{d^2\sigma}{d\theta d\nu} \propto F_2^N(x) = \sum e_q^2 x f_q^N(x)$$





- $F_2^N(x)$ is the structure function (observable!)
- $f_q^N(x)$ is the Parton Distribution Function
- $x \equiv x_B = \frac{Q^2}{2P\cdot q} \xrightarrow[\text{LAB frame}]{} \frac{Q^2}{2M\nu} \xrightarrow[\text{IMF frame}]{}$ longitudinal momentum fraction for a quark q in a nucleon N

In principle $F_2^N = F_2^N(x, \mathbf{Q^2})$: in the Bjorken limit $(\nu, Q^2 \to \infty$, i.e. x_B fixed), F_2^N **scales in** x_B

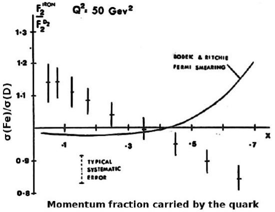
DIS $\longrightarrow$ Incoherent scattering off pointlike partons

The EMC effect

Consider the ratio ($d \approx$ free nucleons)

$$R(x) = \frac{F_2^A(x)}{F_2^d(x)}, x = \frac{Q^2}{2M\nu} \in \left[0; \frac{M_A}{M}\right]$$

The European Muon Collaboration (**EMC**) found $\mathbf{R(x) \neq 1}$



The nuclear medium modifies the inner structure of the bound nucleons.

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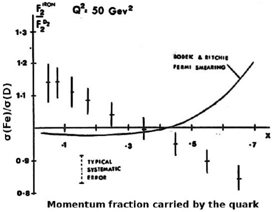

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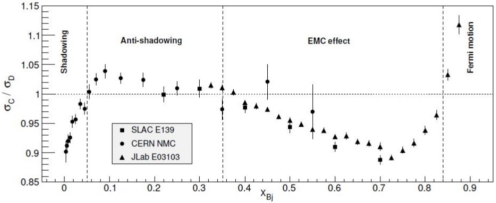

- $x \leq 0.05$: "Shadowing region"
- $0.3 \leq x \leq 0.85$: "EMC region"
- $0.85 \leq x \leq 1$: "Fermi motion region"

Many models but not yet a complete explanation...

(e.g. see **Cloët et al. JPG (2018)**, for a recent report)

How can we better understand the EMC effect?

- ***Elastic scattering*** $\longrightarrow$ **Form factors** $F(\Delta^2)$ $\longrightarrow$ no inner parton structure, only spatial extent

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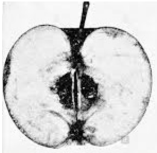
- **????** $\longrightarrow \mathcal{F}_q(x, Q^2, ??..)$ $\longrightarrow$ *Transverse coordinate plane and momentum space*



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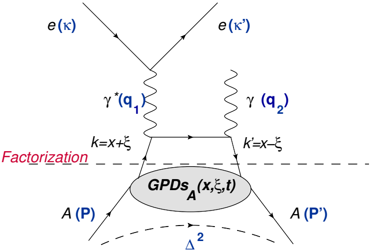
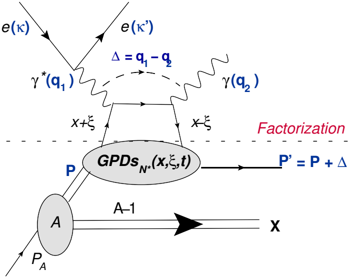
- ***Inclusive DIS*** $\longrightarrow$ **PDFs** $f_q(x, Q^2)$ $\longrightarrow$ Longitudinal momentum space, no info on the coordinate plane
- **Exclusive processes** $\longrightarrow$ **Generalized parton distributions** $H_q(x, \xi, \Delta^2, Q^2)$ $\longrightarrow$ 3-d structure

We can do a *tomography* of hadrons in coordinate space.

Exclusive processes: DVCS off nuclei in handbag approximation

Two different *channels* for DVCS off nuclei: **coherent and incoherent**





- Factorization property $\Delta^2 \ll Q^2$ (e.g., see **Collins et al., PRD (1997)**) :
  - **HARD PART** $\Longrightarrow$ **perturbative QED & QCD**
  - **SOFT PART** $\Longrightarrow$ **non-perturbative QCD** $\longrightarrow$ **GPDs**
- GPDs depend on: $\left(a^{\pm} = \frac{a_0 \pm a_3}{\sqrt{2}}; \bar{P} = \frac{P+P'}{2} \text{and } \bar{k} = \frac{k+k'}{2}\right)$
  - Δ^2 =t= $(P' - P)^2$ = $(q_1 - q_2)^2$
  - x = $\frac{\bar{k}^+}{\bar{P}^+}$
  - ξ = $-\frac{\Delta^+}{2\bar{P}^+}$
  - Q^2 = $-(\kappa - \kappa')^2$
- $x \leq \xi$: GPDs describe **antiquarks**;$-\xi \leq x \leq \xi$: GPDs describe $q\bar{q}$ **pairs**; $x \geq \xi$: GPDs describe **quarks**

GPDs in a nutshell (i)

GPDs are introduced considering the ***light-cone correlator***:

$$F^A_{S,S'} = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle P'S'|\bar{\psi}\Big(-\frac{z^-}{2}\Big)\gamma^+\psi\Big(\frac{z^-}{2}\Big)|PS\rangle$$
$$= \frac{1}{2\bar{P}^+}\Big[H^A_q(x,\xi,t)\bar{u}(P',S')\gamma^+u(P,S) + E^A_q(x,\xi,t)\bar{u}(P',S')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(P,S)\Big]$$

1) Form factor

$$\sum_N \int_{-1}^{1} dx \sum_q e_q H^A_q(x,\xi,t) = F^A_1(t)$$

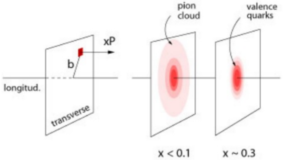
2) PDFs (when $P = P'$, i.e $t = \xi = 0$)

$$H^A_q(x,0,0) = q^A_q(x) \qquad x > 0$$
$$H^A_q(x,0,0) = -\bar{q}^A_q(-x) x < 0$$

3) Probabilistic interpretation in *impact parameter space* (**Burkardt, PRD (2000)**)

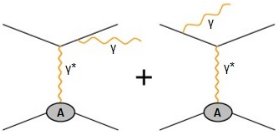
$$\rho^q(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H^A_q(x,0,\Delta^2_\perp)$$

Toward the explanation of the EMC effect



- At JLab kinematics, ***Bethe Heitler*** process interferes with DVCS enhancing this latter. For this reason, it is convenient to measure **asymmetries**, e.g.

$$A_{LU} = \frac{\sigma^{\lambda=+} - \sigma^{\lambda=-}}{\sigma^{\lambda=+} + \sigma^{\lambda=-}}$$



$$\sigma^{\lambda} \propto T_{BH}^2 + T_{DVCS}^2 + \mathcal{I}_{BH-DVCS}^{\lambda}$$

that can be expressed in terms of

  - **Form Factors**

$$T_{BH} \propto FF(\Delta^2)$$

  - **Compton Form Factors** ($CFFs \propto$ GPDs)

$$T_{DVCS} \propto \mathcal{H}(\xi, \Delta^2) = \int_{-1}^{1} dx \frac{H_q^A(x, \xi, \Delta^2)}{x - \xi + i\epsilon} = \Re e\mathcal{H}(\xi, \Delta^2) + i\Im m\mathcal{H}(\xi, \Delta^2)$$

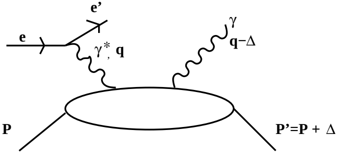
  To de-convolute GPDs we need a wide range in t and ξ otherwise a model input is needed $\longrightarrow$ first results for proton's tomography **Dupré et al. PRD (2017) 95, p. 01150**

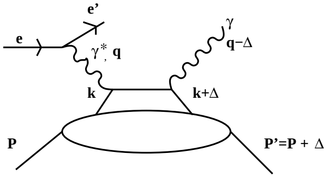
- DVCS is sensitive only to chiral-even GPDs and is dominated by quark GPDs in the valence region.

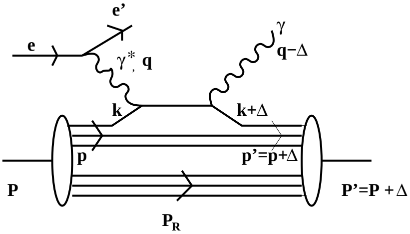
Why nuclei?

Coherent DVCS channel

Handbag approximation







Impulse approximation (IA)

Impulse approximation in light nuclei

As a good starting point, let us consider the **IA** (in a second step we can add as many refined ingredients as we want) whose validity has been experimentally confirmed at JLab kinematics in, e.g., **Slifer et al. PRL (2008) 022303.**

Let us start from the light-cone correlator where we insert two complete sets of states

- the active nucleon (kinematically off-shell)
- the remnant $A-1$-body system

We get a **convolution formula for the GPD** $H_q^A(x,\xi,\Delta^2)$, $\left(z = \frac{\text{long. } N \text{ mom. fraction}}{\text{long. } q \text{ mom. fraction}}\right)$

$$H_q^A(x,\xi,\Delta^2) \approx \sum_N \int \frac{dz}{z} h_N^A(z,\xi,\Delta^2) H_q^N\left(\frac{x}{z},\frac{\xi}{z},\Delta^2\right)$$

where the **off-diagonal light-cone momentum distribution** is

$$h_N^A(z,\xi,\Delta^2) = \int dE d\vec{p} P_N^A(\vec{p},\vec{p}+\vec{\Delta},E)\delta\left(z - \frac{\bar{p}^+}{\bar{P}^+}\right)$$

$P_N^A(\vec{p},\vec{p}+\vec{\Delta},E)$ is the **one body off-diagonal spectral function** of the nucleon N in the nucleus A

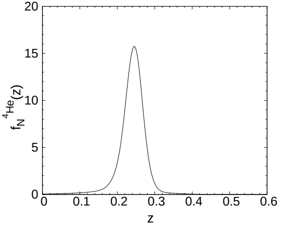
The **forward limit** (i.e. $\xi, \Delta^2 \to 0$) of the light-cone momentum distribution

$$h_N^A(z,0,0) = f_N^A(\tilde{z}) = \int dE \int d\vec{p} P_N^A(\vec{p},E)\delta\left(\tilde{z} - \frac{p^+}{P^+}\right)$$

and the forward limit of the GPD becomes:

$$H_q^A(x,0,0) = q_q^A(x) \approx \sum_N \int_1^x \frac{d\tilde{z}}{\tilde{z}} f_N^A(\tilde{z}) q_q^N\left(\frac{x}{\tilde{z}}\right)$$

where $f_N^A(\tilde{z})$ strongly picked around $\tilde{z} \approx 1/A$



For ^{4}He, $f_N^A(z)$ picked at $z \approx 0.25$

How can the nuclear effects be inferred from $f_N^A(z)$?

ξ is the fraction of "+" momentum transfer and cannot exceed the width of $f_N^A(z)$ to have the target intact after the interaction.

If DVCS were observed in a wide range of t (ξ), exotic effects beyond IA, e.g. non-nucleonic d.o.f., would be pointed out (**Berger et al. PRL 87 (2001)**).

Similar effect predicted in DIS at $x_B > 1$, where data are not accurate enough

Issues when dealing with nuclei

When dealing with **nuclear targets**, keep in mind that:

- a system of spin S has $(2S+1)^2$ parton helicity conserving and chiral-even quark GPDs and $(2S+1)^2$ parton helicity flipping and chiral odd quark GPDs
  $\Longrightarrow$ $\mathbf{2(2S+1)^2}$ GPDs. Considering NLO terms, we have $\mathbf{4(2S+1)^2}$ **GPDs**.
- for **light nuclei**, realistic calculations of the wave functions, exact solutions of the Schrödinger equation with **phenomenological NN potentials** (e.g. Av18) and 3-body forces, are possible

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Theoretical challenge: the bigger is *A*, the harder are such calculations

- **Deuteron** ($S=1$): many GPDs yet at leading twist (**Berger et al. PRL (2001)**) evaluated in a light front framework **Cano et al. EPJA (2003)**) also in the transversity sector (**Cosyn et al. PRD (2018)**), access to the neutron in the unpolarized setup of the incoherent channel.
- ^{3}**He** ($S=1/2$): study of the isospin-flavor dependence of nuclear effects (**Scopetta PRC (2004), Scopetta PRC (2009)**), evaluation of its conventional nuclear structure (e.g. **Rinaldi et al. PRC (2012), Rinaldi et al. FBS (2014)**); not yet DVCS data for a ^{3}He target; preliminary results for the observables in **Fucini et al. FBS (2021)**

Why is ^{4}He a golden nucleus?

- ^{4}He is a typical few body system and it is theoretically well known
- exact and realistic calculations are difficult BUT possible
- $J^{\pi}_{^4He} = 0^+$ and $I_{^4He} = 0 \implies$ only one chiral-even GPD at LO
- CLAS and ALERT collaboration are carrying on an experimental program at JLab using ^{4}He target

Coherent (**PRL 119, 202004 (2017)**) and incoherent (**PRL 123, 032502 (2019)**) DVCS off ^{4}He has been measured at the Jefferson Laboratory!

- good perspectives at **JLab with a 12 GeV** electron beam and the forthcoming **EIC**

Our point is to obtain models able to distinguish "conventional" and "exotic" nuclear structure effects

Coherent DVCS off ^{4}He

A convolution formula for the chiral even GPD H_q can be obtained in terms of:

- **GPDs of the inner nucleons**

$$H_q^{^4He}(x,\xi,\Delta^2) = \sum_N \int_{|x|}^1 \frac{dz}{z} h_N^{^4He}(z,\xi,\Delta^2) \; \mathbf{H_q^N}\left(\frac{x}{\zeta}, \frac{\xi}{\zeta}, \Delta^2\right)$$

- **light-cone momentum distribution**

$$h_N^{^4He}(z,\Delta^2,\xi) = \frac{M_A}{M} \int dE \int_{p_{min}}^{\infty} dp \int_0^{2\pi} d\phi \, p \, \tilde{M} P_N^{^4He}(\vec{p}, \vec{p}+\vec{\Delta}, E)$$

$$\xi_A = \frac{M_A}{M}\xi \, , \, \tilde{z} = z + \xi_A \, ,$$

$$\tilde{M} = \frac{M}{M_A}\left(M_A + \frac{\Delta^+}{\sqrt{2}}\right), p_{min} = f(z,\xi_A,E), \mathbf{H_q^N} = \sqrt{1-\xi^2}[H_q^N - \frac{\xi^2}{1-\xi^2}E_q^N]$$

One needs the **non-diagonal spectral function** and the **nucleonic GPDs** (we used the Goloskokov-Kroll models **(EPJ C (2008)- EPJ C (2009))**

The ^{4}He spectral function: off diagonal case

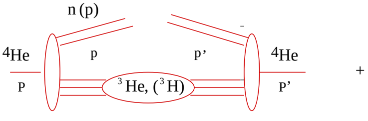
$$P_N^{^4He}(\vec{p}, \vec{p}+\vec{\Delta}, E) = \rho(E) \sum_{\alpha\,\sigma} \langle P+\Delta| - p\, E\, \alpha, p+\Delta\, \sigma\rangle\langle p\,\sigma_N, -p\, E\, \alpha|P\rangle$$

with ***removal energy*** $E = |E_A| - |E_{A-1}| - E^*$

Ground-state contributions

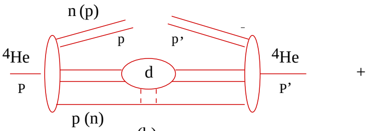
2-body channels

- $\langle^4$ He $|$p, ^{3}H $\rangle$;
- $\langle^4$ He $|$n, ^{3}He $\rangle$;

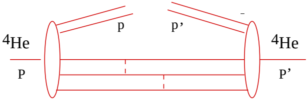


(a)

Excited-state contributions



(b)



(c)

3-body channels

- $\langle^4$ He $|$p, d n$\rangle$;
- $\langle^4$ He $|$n, d p $\rangle$;

4-body channels

- $\langle^4$ He $|$n, p n p$\rangle$;
- $\langle^4$ He $|$p, n p n $\rangle$.

Our model for the spectral function (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

$$
\begin{aligned}
P_N^{^4He}(\vec{p}, \vec{p}+\vec{\Delta}, E) &= n_0(\vec{p}, \vec{p}+\vec{\Delta})\delta(E) + P_1(\vec{p}, \vec{p}+\vec{\Delta}, E) \\
&= n_0(|\vec{p}|, |\vec{p}+\vec{\Delta}|, \cos\theta_{\vec{p},\vec{p}+\vec{\Delta}})\delta(E) + P_1(|\vec{p}|, |\vec{p}+\vec{\Delta}|, \cos\theta_{\vec{p},\vec{p}+\vec{\Delta}}, E) \\
&\simeq a_0(|\vec{p}|)a_0(|\vec{p}+\vec{\Delta}|)\delta(E) + \sqrt{n_1(|\vec{p}|)n_1(|\vec{p}+\vec{\Delta}|)}\delta(E-\bar{E})
\end{aligned}
$$

- the total momentum distribution is $n(p)$

$$n_1(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|)$$

- $n_0(k)$ is the momentum distribution when the recoiling system in the ground-state

$$n_0(|\vec{p}|) = |a_0(|\vec{p}|)|^2$$

  with

$$a_0(|\vec{p}|) = \langle \Phi_3(1,2,3)\chi_4\eta_4 | j_0(|\vec{p}|R_{123,4})\Phi_4(1,2,3,4)\rangle \, .$$

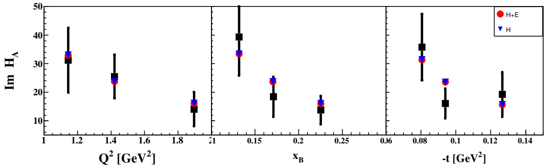
- $\boldsymbol{n(p)}$ has been evaluated for the 4-body and 3-body systems within the Av18 NN interaction **(Wiringa et al., PRC (1995))** + UIX 3-body forces **(Pudliner et al., PRL (1995))**
- $\bar{E}$ is the average excitation energy of the recoiling system (the model for the excited part of the diagonal s.f. **M. Viviani et al., PRC (2003)** is a realistic update of the model of **Ciofi et al., PRC (1996)**, i.e. $P_N^{1\,\text{our model}} = N(p)P_N^{1\,\text{Ciofi's model}}$)

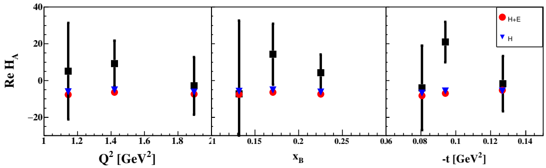
Coherent DVCS: a comparison with EG6 data, $\mathcal{H}_A$ (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

$$\Im m \mathcal{H}_A(\xi,t) = \sum_{q=u,d,s} e_q^2 (H_q^A(\xi,\xi,\Delta^2) - H_q^A(-\xi,\xi,\Delta^2))$$

$$\Re e \mathcal{H}_A(\xi,t) = \Pr \sum_{q=u,d,s} e_q^2 \int_0^1 \left(\frac{1}{\xi+x} + \frac{1}{x-\xi}\right)(H_q^A(x,\xi,t) - H_q^A(-x,\xi,t))$$

Black squares → JLab data from the CLAS coll. (**Hattawy et al., PRL (2018)**)





Coherent DVCS: a comparison with EG6 data, A_{LU} (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

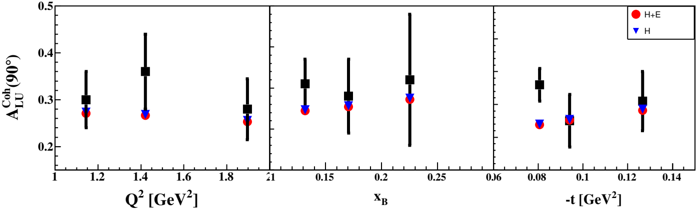
Beam spin asymmetry as a function of azimuthal angle $\phi = 90^o$

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}.$$

where $\alpha_i(\phi)$ are kinematical coefficients from **A. V. Belitsky et al., Phys. Rev. D 79, 014017 (2009)**.

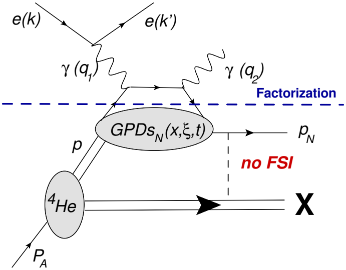
From left to right, the quantity is shown in the experimental Q^2, x_B and $-t$ bins

Results of our approach VS **EG6 data**



Incoherent DVCS off ^{4}He

Framework for incoherent DVCS off ^{4}He in IA (S. F., S. Scopetta, M. Viviani, PRD 01, 071501 (2020)- PRC 102, 065205 (2020))



The **beam spin asymmetry** (BSA) measured is:

$$A_{LU} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

where

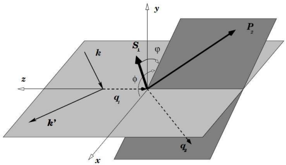
$\pm$refers to positive(negative) beam polarizations.

Fundamental starting points for our **Impulse Approximation** approach are:

- kinematical **off shellness**:
  $p_0 = M_A - \sqrt{M_{A-1}^{*\,2} + \vec{p}^2} \simeq M_N - E - T_{rec} \implies p^2 \neq m^2$
- general expression for **cross section**

$$(d\sigma^{\pm})_{INC} = (2\pi)^4 \frac{1}{2P_A \cdot k} \sum_N \sum_X |\mathcal{A}^{\pm}|^2 \delta^4(P_A + k - k' - p_X - p_N - q_2) LIPS$$

where $LIPS = d\tilde{p}_X d\tilde{k}' d\tilde{q}_2 d\tilde{p}_N$



In a frame where the target nucleus is at rest, the cross section and its azimuthal dependence are expressed in terms of a ***convolution formula*** between:

- the **diagonal** spectral function

$$d\sigma^{\pm}_{Incoh} = \int_{exp} dE d\vec{p} \frac{p \cdot k}{p_0 |\vec{k}|} \; P^{^4He}(\vec{p}, E) \; d\sigma^{\pm}_b(\vec{p}, E, K)$$

- the DVCS cross section off a bound proton

The differential cross section appearing in A_{LU} is

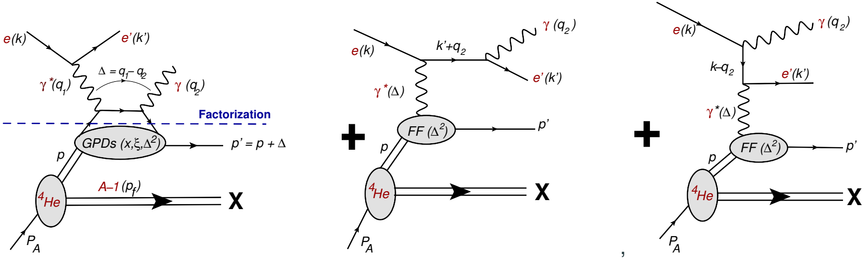
$$\frac{d\sigma^{\pm}_{Incoh}}{dx_B dQ^2 d\Delta^2 d\phi} = \int_{exp} dE d\vec{p} \, P^{^4He}(\vec{p}, E) |\mathcal{A}^{\pm}(\vec{p}, E, K)|^2 g(\vec{p}, E, K)$$

where

- $\boldsymbol{K} = \{x_B = \frac{Q^2}{2M\nu}, Q^2, \phi, \Delta^2\}$ fixes the proper range of integration
- $\boldsymbol{g(\vec{p}, E, K)}$ arises from the integration of LIPS and includes also the flux factor

Our formalism (ii)

Schematically $d\sigma^{\pm} \approx \int d\vec{p} dE P^{^4He}(\vec{p}, E)|A^{\pm}(\vec{p}, E, K)|^2$ with
$|\mathcal{A}^{\pm}|^2 = \mathcal{T}^2_{BH} + \mathcal{T}^2_{DVCS} + \mathcal{I}^{\pm}_{DVCS-BH}$.



The BSA for the incoherent DVCS reads:

$$A^{Incoh}_{LU}(K) = \frac{\mathcal{I}^{^4He}(K)}{T^{2\,^4He}_{BH}(K)}$$

$$\mathcal{I}^{^4He}(K) = \int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, g(\vec{p}, E, K)\, \mathcal{I}(\vec{p}, E, K)$$

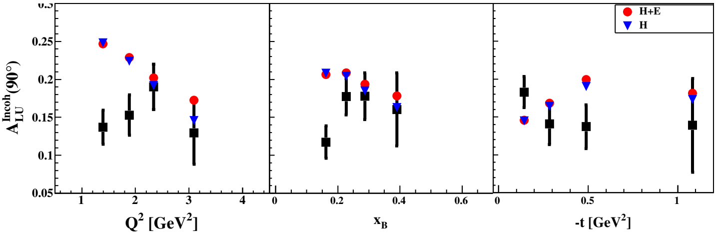
$$T^{2\,^4He}_{BH}(K) = \int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, g(\vec{p}, E, K) T^2_{BH}(\vec{p}, E, K)$$

$$A_{LU}^{Incoh}(K) = \frac{\mathcal{I}^{^4He}(K)}{T_{BH}^{2\,^4He}(K)}$$

- Our expression for $|\mathcal{T}_{BH}(\vec{p}, E, K)|^2 = c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi)$ is a generalization for a moving bound nucleon of results by **Muller et al., NLB (2002)**
- the interference BH-DVCS $\mathcal{I}(\vec{p}, E, K) \approx s_1^{\mathcal{I}}(\vec{p}, E, K)\Im m\mathcal{H}(\xi', \Delta^2, Q^2)$.
- For the proton GPD H_q^N, again, we used **GK model** evaluated for $\xi' = \frac{Q^2}{(p+p_N)(q_1+q_2)} \neq \frac{x_B}{2-x_B} = \xi_{rest}$
- No nuclear modifactions occur for the **form factors** of the bound proton
- For the diagonal spectral function $P^{^4He}(\vec{p}, E)$ we use an Av18-based model (**M. Viviani et al., PRC 67, 034003 (2003)**)
  - the ground-state of the recoiling system is described in terms of exact wave functions for the 4-body and 3-body systems
  - the excited state of the recoiling system is an update of the 2-nucleon correlation model by **Ciofi et al., PRC 53 1689 (1996)**.

Incoherent DVCS: results

- Our results are compared with the experimental data from EG6 collaboration at JLab (**M. Hattawy et al., PRL 123, 032502 (2019)**).
  From left to right, the quantity is shown in the experimental Q^2, x_B and $-t$ bins

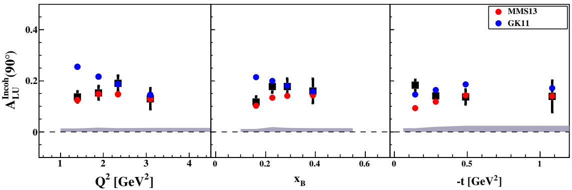


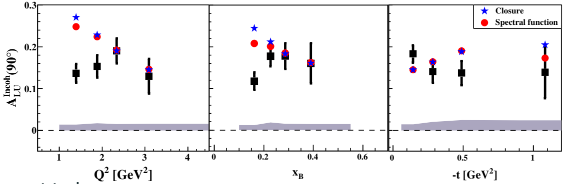
✓ **Good agreement in the region of high Q^2**

An analysis of the interplay between the t and Q^2 dependence could reveal if FSI effects could be responsible of the disagreement in low Q^2 region

Testing the IA

Let us consider the **MMS13 model** (**Mezrag et al., PRD (2013)**) for the proton GPD and the **closure approximation** (fixed removal energy $\Longrightarrow$ momentum distribution)





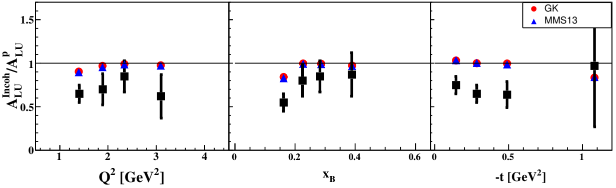
Our BSA turns out to be :

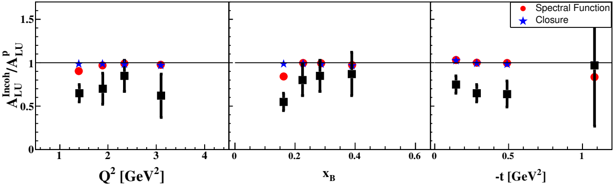
- sensitive to the nucleonic model used, in particular at low values of Q^2
- mildly sensitive to the details of the nuclear model used in the calculation

Nuclear dynamics in $|BH|^2$ and in the BH-DVCS interference

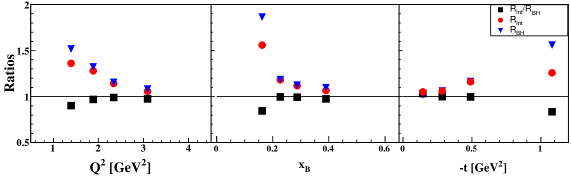
Are the nuclear effects measured depending on the modification of the bound proton partonic structure? Let us consider the ratio

$$A_{LU}^{Incoh}/A_{LU}^{p} = \frac{\mathcal{I}^{4He}}{\mathcal{I}^{p}}\frac{T_{BH}^{2\ p}}{T_{BH}^{2\ 4He}} = \frac{R_I}{R_{BH}} \propto \frac{(nucl.eff.)_{\mathcal{I}}}{(nucl.eff.)_{BH}},$$





Using the GK models and the spectral function

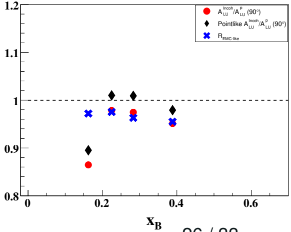


Nuclear dynamics modify both $|T_{BH}|^2$ and $\mathcal{I}_{BH-DVCS}$ but in the ratio these effects **compensate** each other

This fact hasn't to do with a modification of the **parton structure**

as confirmed by:

- the ratio $A_{LU}^{Incoh}/A_{LU}^{p}$ for **"pointlike" protons**
- the **"EMC-like" trend**



$$R_{EMC-like} = \frac{1}{\mathcal{N}} \frac{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, \Im m\, \mathcal{H}(\xi', \Delta^2)}{\Im m\, \mathcal{H}(\xi, \Delta^2)}$$

DVCS off light nuclei at the EIC

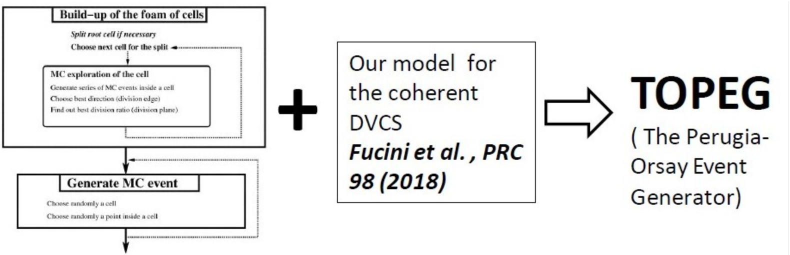
Hadronic Physics at the EIC

- **JLab** (fixed target experiments)$\longrightarrow$ mostly x_B valence region
- A worldwide community (+ 1000 users) and a strong activity for a global project: the **Electron Ion Collider** (EIC)

A groundbreaking boost in our knowledge at the EIC in the next decades where DVCS is a key process (exclusive reactions WG)

- Large range of center-of-mass energies and very high **luminosity** $\longrightarrow$ high precision measurements
- **Polarization of nuclear beams** $\longrightarrow$ spin asymmetries (e.g ^{3}He can be actually used as a neutron target)
- ... not only nuclear tomography
  - **Role of gluon GPDs and shadowing effects**: possible gluon d.o.f. in nuclei will be accessible at very small values of x_B (**Goeke et al. PRC (2009)**)
  - Study of the **nuclear energy momentum tensor** and the **distribution of pressure and shear forces** inside the nucleus (**M.V. Polyakov, PLB (2003)**): from the energy-momentum tensor, the total angular momentum of the target can be accessed.

TOPEG (**T**he **O**rsay-**P**erugia **E**vent **G**enerator) is a Root based generator (**S. Jadach (2005)**) + **our model** for the coherent DVCS



- Check for JLab 6 GeV
- We generated events for the three energy configurations for the DVCS off ^{4}He at the EIC
  - 5x41 GeV
  - 10x110 GeV
  - 18x110 GeV
- These results will be included in the **Yellow Report of the EIC user group** (to be released by the end of this month)

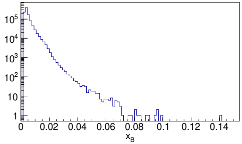
18 x 110 GeV: kinematical distributions

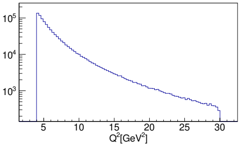
We generated events weighted by the cross section $\frac{d^4\sigma}{dQ^2 dt d\phi dx_B}$

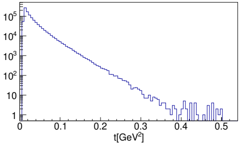
- 1 million events
- in the x-section, we set $\Re e$(CFF)=0 (limitation in the computation time)
- Luminosity: 250 nb^{-1} (**NOT ENOUGH!!**)
- $Q^2 > 2$ GeV^2 , $y < 0.8$, $t_{min} < |t| < t_{min} + 0.5$ GeV^2

For small $|t|$, we expect an enhancement of the cross section for the dominance of the BH process ($\simeq \mathbf{FF^2}$).

$$|t_{min}| = \frac{4M_{^4He}^2 \xi^2}{1-\xi^2} \quad \text{with} \quad \xi = \frac{x_B}{2-x_B} \quad \text{and} \quad x_B = \frac{Q^2}{y(s-M_{^4He})}$$







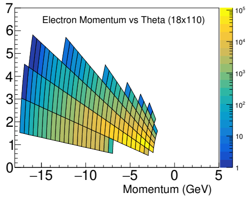
18x110 GeV: analysis

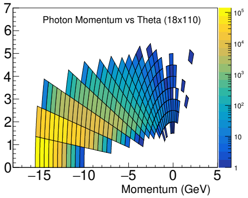
Is there plenty of room to study the region around the first diffraction minimum in the ^{4}He FF ($t_{\mathrm{dif.\,min}} = -0.48$ GeV^2)?

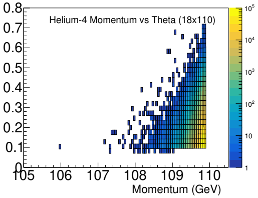
- 99%+ electrons and photons are in the acceptance of the detector matrix
- This is true for all energy configurations

> Electrons and photons appear in easily accessible kinematics according to the detector matrix requirements (exceptions for small angles photons)

- Acceptance at low -t will be cut passing through the detectors
  - t_{min} is set by the detector features (i.e. the Roman pots capabilities)
  - t_{max} is fixed by the luminosity (billion of events to generate)







Conclusions and outlooks

Our workable approaches to DVCS off ^{4}He allow to constrain conventional nuclear effects.

Formal development of a theoretical formula for the chiral even **GPD** of the ^{4}He with an overall good agreement with JLab data

Calculation of the **beam spin asymmetry of a bound proton and study of the nuclear effects**

Concerning the nuclear ingredient, to date we have a s.f.:

- Realistic AV18 + UIX momentum dependence
- Dependence on E, angles and Δ in the s.f is modeled and not yet realistic

Version 1.0 of `TOPEG` for a key process at the EIC to make predictions about the cross sections, contributing to the **physical program** and the **design** of the EIC

> Our approach is helpful for planning new measurements, not only for interpreting the present data.

Outlooks and future perspectives

Evaluation of the incoherent channel considering **Final State Interaction** effects (tagged experiments by **ALERT collaboration**)

Need for covariance: relativistic description for both DVCS channels in a **light-front scenario** to achieve polinomiality for GPDs and sum rules in DIS (in our approach, number of particles and momentum sum rule not fulfilled at the same time)

A full realistic evaluation of the **(off)-diagonal spectral function**

Concerning **TOPEG**:

- Preliminary results for the **projections for the ^{4}He profiles**
- Study the impact of **non nucleonic d.o.f.**: is this Physics accessible at the EIC ?
- Re-do the simulations for $\Re e$(CFF)$\neq 0$ (tech improvements and possible parallelization to shorten the calculation time and get higher luminosity)
- Include **shadowing effects** at low x_B
- Plug-in **other light nuclei targets** and the proton (**free** and **bound**) target
- Add other hard processes?

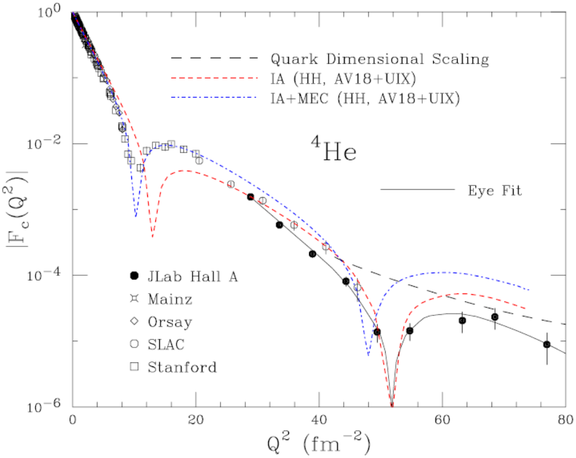
Thank you ...

Questions?

Backup slides

Form factor of the ^{4}He at high Q^2

Red dashed line: One body part of the form factor from a direct integration of the diagonal momentum distribution of the ^{4}He within Av18+UIX calculation (figure from **Phys. Rev. Lett. 112, 132503**)



EMC effect with our model for the off diagonal spectral function

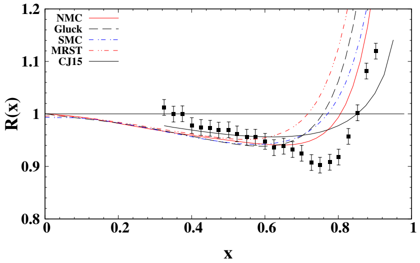
$$R(x) = \frac{F_2^{^4He}(x)}{F_2^d(x)} \qquad x \in [0 : M_A/M]$$

where the **function structures** F_2 for $A = {}^4$He,d are defined as

$$F_2^A(x) = \sum_N \int_x^{M_A/M} dz f_N^A(z) F_2^N\left(\frac{x}{z}, Q^2\right)$$

in terms of the *light-cone momentum distribution*

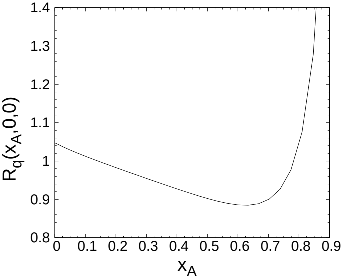
$$f_N^A(z) = \int d\vec{p} \int dE P_N^A(\vec{p}, E) \frac{p^+}{p_0} \delta\left(z - \sqrt{2}\frac{p^+}{M_A}\right)$$



- Our model isn't predictive at small x
- Good agreement in the valence region
- Strong dependence on the model for F_2^N at large x
- Need to better unravel the Q^2 dependence of $R(x)$

Data from **Seely et al., PRL (2009)**

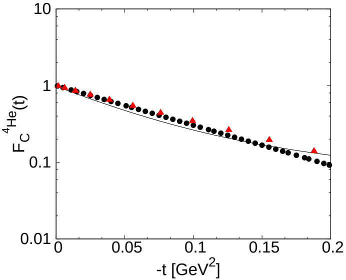
Some checks for our model for the coherent DVCS off ^{4}He



- **EMC-like effect**

$$R_q(x,0,0) = \frac{H_q^A(x_A,0,0)}{2(H_q^p(x_A,0,0)+H_q^n(x_A,0,0))}$$

✓ Good EMC-like behavior;



- **Charge form factor**

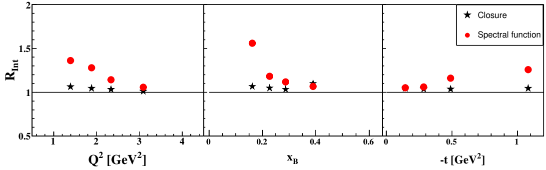
$$F_C^{^4He}(\Delta^2) = \frac{1}{2}\sum_q e_q \int_0^1 dx H_q^{^4He}(x,\xi,\Delta^2)$$

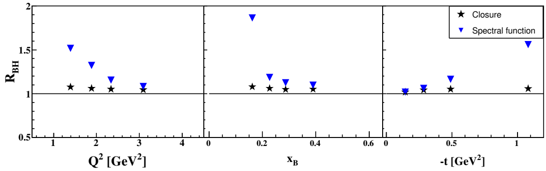
Data (●) from **PRC 160, 4 (1987)**, theoretical one-body calculation (▲) by **Marcucci et al., PRC 58, 3069 (1998)**.

✓ Good agreement with the experimental data.

Why choose the treatment with the spectral function

The effects in the numerator and in the denominator of A_{LU}^{Incoh} compensate each other in the ratio. In the **closure approximation,**





- the **removal energy is fixed** to an average value
- the **change of the off-shellness** of the proton produce a big effect in each amplitude

If the nuclear dynamics modifies the amplitudes, the effect can be big even if the parton structure of the bound proton doesn't change